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Review

A review of climate change implications for built environment: Impacts, mitigation measures and associated challenges in developed and developing countries

Ivan Andrić, Muammer Koc, Sami G. Al-Ghamdi*

Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University, Doha, Qatar

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ABSTRACT

This interdisciplinary review organizes, summarizes and critically analyzes the literature regarding the nexus between climate change and the built environment, its associated impacts, and the proposed mitigation measures and challenges for their implementation. While global warming-driven changes of ecosystems could have multiple impacts on the built environment (most prominently on building energy demand and related urban energy systems), the building sector presents significant potential for climate change mitigation. Study findings indicate that building renovations have significant potential for the mitigation of urban-related emissions and achieving the sustainability goals set. However, these measures should be adapted to different climate conditions and different segments of the building stock. In developed countries, where the majority of the building stock is older than 50 years, more effort should be invested into creating adequate policies for the renovation of existing building stock. In developing countries with rapid growth in the urban environment, due to a previous lack of energy-efficiency policies, the focus should be on policy development and an increase in environmental awareness among building owners/tenants. Moreover, additional research efforts should be invested into performing technoeconomic and environmental analyses of green wall performance under future climate conditions, especially within the hot and humid climates.

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* Corresponding author.
E-mail address: salghamdi@hbku.edu.qa (S.G. Al-Ghamdi).

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Abbreviations used

EPS	Expanded Polystyrene
GCC	Gulf Cooperation Council
GCM	Global Circulation Model
GIS	Geographic Information System
KSA	Kingdom of Saudi Arabia
LiDAR	Light Detection and Ranging
SABO	Swedish Association of Housing Companies (Sveriges Allmännyttiga Bostadsföretag)
UAE	United Arab Emirates
WWR	Window-to-Wall ratio
XPS	Extruded Polystyrene

Nomenclature used

$E_{t,rf}$	Reference total building environmental impact
E_{cs}	Environmental impact of building construction
$E_{op,rf}$	Reference environmental impact of building operation
$E_{elf,rf}$	Reference environmental impact of recycling/landfilling
E_{rf}	Building environmental impact prior to renovation
E_{rn}	Environmental impact of building renovation
$E_{op,rn}$	Environmental impact of building operation after renovation
$E_{elf,rn}$	Environmental impact of recycling/landfilling after renovation
$E_{t,rn}$	Total building environmental impact after renovation
t_{lf}	building lifetime period
t_{cs}	building construction period
t_{op}	building operation period
$t_{op,r}$	building operation period prior to renovation
$t_{op,rn}$	building operation period after renovation
t_{elf}	recycling/landfilling period

1. Introduction and background

1.1. Climate change and the urban environment nexus

Climate change has been verified by measured air and ocean temperatures, extensive snow and ice melting, and the rise in average ocean and sea level (IPCC, 2014). The influence of anthropogenic factor on the climate system is obvious—anthropogenic-related greenhouse gas emissions had a thirty-six-fold increase since the beginning of the industrial era, and the majority of research studies indicate that anthropogenic drivers have been the dominant cause of global warming (IPCC, 2014). The nexus between climate change and the built environment is complex and intertwined as depicted in Fig. 1. On the one hand, the built environment is vulnerable to climate change. Potential impacts can be categorized into four main groups: impacts on building structures (caused by environmental catastrophes such as floods, landslides, storms, and excess snow load), building construction (decay of fastening and water supply systems), building material properties (diminished performance of frost-resistance, UV-resistance, and insulation due to material decay), and indoor climate/energy use (increase in indoor temperatures and relative humidity levels), as elaborated by Hacker et al. (2005) and Hrabovszky-Horváth et al. (2013). This review focuses on the relationship between climate change and energy use in buildings. Such relationship is reciprocal - due to the current energy consumption levels, the building sector has higher climate change impacts, hence mitigation potential, than any other sector (Dalla Mora et al., 2018), with potential savings of 42% in energy use and 35% in greenhouse gas emissions, and reduction of material extraction by more than 50% (Sierra-Pérez et al., 2018). According to the International Energy Agency (International Energy Agency, 2007) and the study by Seyboth et al. (2008), building heating and cooling services account for more than 30% of global energy consumption. However, the share of the building sector in energy consumption and CO_2 emissions in developed and developing countries is significantly higher. For example, the building sector in the U.S. is responsible for approximately 40% of total energy use on a national level, where at least 65% of energy in buildings is consumed for heating, cooling, and lighting services (U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, 2010; U.S. Energy Information and Administration, 2012). In Europe, the building sector accounts for more than 40% of the European Union's energy consumption (European Parliament, 2010), despite the relatively moderate climate conditions in the majority of the countries. The main reason for such energy consumption levels is the fact that more than 40% of the European building stock is older than 40 years (European Parliament, 2010; Kylili et al., 2016). The majority of the building stock was erected during the reconstruction wave following World War II in order to mitigate the general housing shortage caused by the war (Eurostat, 2010; Hrabovszky-Horváth et al., 2013). These buildings, most of which were erected during the post-war economic boom of the '60s and '70s, have poor thermal performance and thus require significant amounts of energy to maintain indoor comfort conditions (Eurostat, 2010; Fotopoulou et al., 2018; Schitzer et al., 2014; Shahrokni et al., 2014; Xing et al., 2011). In regions with extreme climate conditions, such as hot climates in MENA (Middle East and North Africa) countries, the levels of building energy consumption are even higher, especially in the GCC (Gulf Cooperation Council) countries that have a high growth rate of urbanization. For example, in Qatar, cooling in buildings account for more than 50% of total energy consumption (Bayram et al., 2018; Kharseh and Al-Khawaja, 2016). Buildings in the Kingdom of Saudi Arabia (KSA) consumed about 65% of total electricity produced, which was 47% higher than the world average for the same year, 2010 (Alaidroos and Krarti, 2015; Said et al., 2003). In Kuwait, the building sector accounts for almost 70% of the total primary energy consumption, with 45% of total electricity consumption being attributed to air-

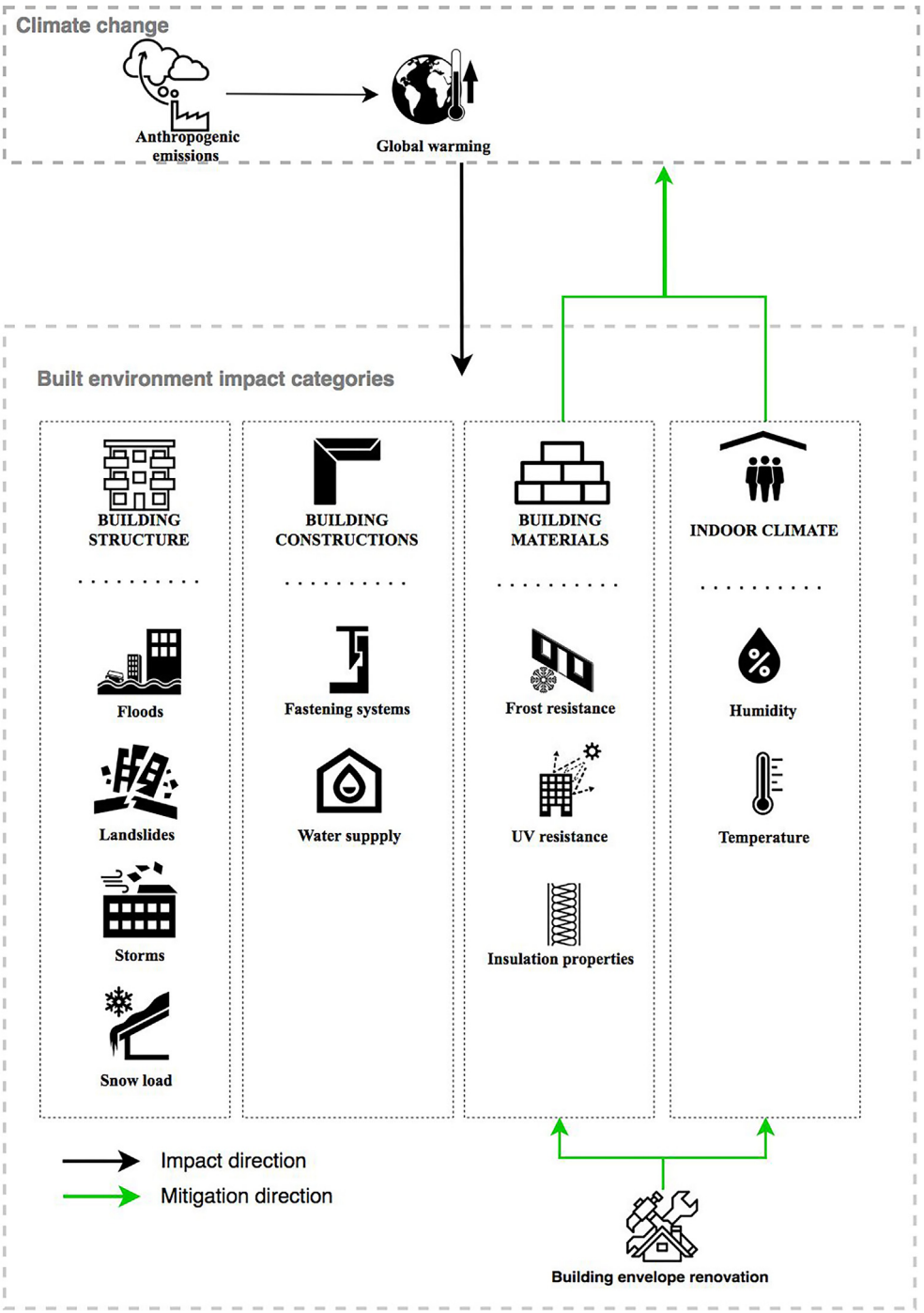

Fig. 1. Climate change and the built environment nexus.

conditioning systems (Ameer and Krarti, 2016; Kuwait Ministry of Electricity and Water, 2014, 2010). Dabaieh et al. (2015) reported that in countries with hot climates such as Egypt, 70–80% of total energy consumption is used in order to operate mechanical cooling systems.

1.2. Future implications and proposed mitigation measures

Without mitigation measures, building sector-related emissions could significantly increase in the future, considering that there is a high probability that outdoor temperatures will increase, with peak heat waves occurring more often and lasting longer in the future (IPCC, 2014), increasing the demand for cooling and thus building energy consumption. Additionally, according to the findings of NOAA (National Oceanic and Atmospheric Administration), colder seasons are warming at faster rate than warmer seasons (Arndt, 2014), which could result in reduced heating and increased cooling season duration even for more temperate climates. Moreover, significant growth of urban environments is predicted in the decades to come due to a rapid population increase (according to UN report (United Nations, 2015), the global population will reach 10 billion by 2056) and

migrations from rural to urban areas (by 2050, the current urban population of 3.9 billion could reach 6.4 billion (International Organization for Migration, 2015)). This aspect is particularly important in developing countries—for example, in Qatar, the population grew from 676,498 in 2002 to 2,529,048 in 2018 (out of which, 92% live in the capital city, Doha), which is an increase of 245% over a 16-year period (Qatar Ministry of Development Planing and Statistics, 2018).

In order to impose efficient energy use in new buildings, many countries have developed and implemented building energy codes, which dictate energy-efficiency requirements for new buildings. In European Union, for example, following the 91/2002/EC directive on building energy performance, all member states developed energy codes for their building stock (Hrabovszky-Horváth et al., 2013). Additionally, a communication report between the European Commission and European Parliament entitled "Roadmap for moving to a competitive low carbon economy in 2050" (European Comission, 2011) implies that significant efforts are necessary in order to reduce building energy consumption (Caputo and Pasetti, 2017). Moreover, European cities are investing significant effort into improving their energy efficiency. According to the analysis performed by Reckien et al. (2018), out of 885 cities across the 28 European countries considered within the study, over 66% have developed some form of an energy-efficiency plan. On the other hand, in GCC countries, the thermal performance and energy consumption of the building sector was initially neglected by local energy authorities, and as a consequence, such a lack of energy-efficiency standards and regulations has increased building energy consumption furthermore over the last decade (Kharseh and Al-Khawaja, 2016). However, in the last couple of years, energy authorities in GCC countries have focused on developing energy-efficiency policies, including the building energy codes (such as Tarsheed initiative for example, Qatar's national program for conservation and efficient use of water and electricity).

While imposing strict energy requirements for new buildings could resolve the issue for the building stock currently in development, achieving the efficiency goals for the existing building stock in developed countries, presents quite a challenging task. In such countries, the majority of the building stock is older than 40 years (Eurostat, 2010; Kylili et al., 2016) and the rate at which old buildings are progressively replaced by new ones is almost negligible (0.05%–0.1% of the total building stock (Thomsen and Van Der Flier, 2009)). A widely acknowledged mitigation measure is the implementation of large-scale building renovation measures. By improving the energy efficiency of the building envelope, heat exchange between the outdoor and indoor environment decreases, reducing the amount of heating and cooling energy required to reach indoor comfort conditions, and consequently reducing building energy consumption. For example, Sweden's national strategy for building stock renovation states that 75% of the current building stock (approximately 1.8 million apartments) will need comprehensive renovations by 2050 in order to meet the energy saving goals set, which implies a renovation rate of 52,000 apartments per year (Palm and Reindl, 2016). Additionally, the Swedish Association of Housing Companies (SABO: Sveriges Allmännyttiga Bostadsföretag) reported that the renovation of post-World War buildings in Sweden could not only significantly reduce national energy consumption, but also improve the quality of life within the renovated neighborhoods, making them more attractive and secure (Johansson et al., 2017; Sveriges Allmännyttiga Bostadsföretag, 2009). In the United Kingdom, it has been estimated that at least 600,000 homes should be renovated each year in order to meet the national 2050 carbon reduction targets (Energy Saving Trust, 2010; Fawcett et al., 2011).

1.3. Challenges for the implementation of proposed mitigation measures

While the large-scale application of suggested renovation measures, which are in accordance with building energy codes, could have additional benefits, such as reduction in renovation time due to the high degree of prefabrication options for materials and elements used for renovations, the process still faces many challenges that currently hinder the process. For example, while the suggested renovation rate in the U.K. is 600,000 homes per year, in reality, less than 1000 homes are annually renovated in accordance with the suggested energy-efficiency standards (Fawcett et al., 2011)). This poses the following question: what obstacles and challenges are hindering the large-scale building renovation process, and how to overcome them?

In general, sustainability measures should encompass a combination of environmental, economic, and social responsibilities (Taleb and Sharples, 2011), and energy-efficiency policies are frequently criticized for being largely based on the assumed rational behavior of the stakeholders and decision-makers for choosing the most energy-efficient measures and/or implementing them the right way (Palm and Reindl, 2016). Building renovation measures are no exception, and three main challenges can be defined. The first challenge is of a social nature: currently, most tenants and house owners have a low level of knowledge on the topic of sustainability practices, let alone building renovation measures. Hence their motivation for significant renovations is usually at low levels unless the right mix of incentives and regulations are developed. While all stakeholders in the building renovation process have expertise in their own area, their knowledge in the areas of expertise of the other stakeholders involved is rather low, which makes the communication rather difficult. The second challenge is of an economic nature: building renovation measures present a significant initial cost for the building owner and/or tenants, with a relatively long investment return period (ten or more years on average (Johansson et al., 2017)). The third challenge arises from an environmental aspect: renovation measures require the investment of additional resources (insulation material for renovations, its transportation, and landfilling/recycling upon the building demolition) over a building's lifetime, which may increase overall building environmental impacts if the environmental benefits of energy saved during a building's operation do not outweigh the additional impacts caused. Thus, taking into account building energy efficiency, economic, and environmental factors, as well as the relationship of social actors (tenants and house owners) with semiotic aspects embedded in the urban environment (Gieryn, 2002; Palm and Reindl, 2016; Star, 1990; Woolgar, 1991), the successful integration of energy-related building renovations requires a high level of cooperation between various actors and stakeholders that possess expertise in different areas such as building physics, economics, environmental assessment methods, and social sciences (Palm and Reindl, 2016).

1.4. Objectives and review outline

The main scope of this study is to provide in-depth, multidisciplinary insights into climate change implications for the energy performance of the built environment, related impacts, and potential mitigation measures and associated challenges for their implementation in developed and developing countries. Primarily, the scale of climate change impacts on building energy demand in the future is evaluated based on the previous findings available within the current literature. Secondarily, the potential implications of changed demand for building and urban energy systems are discussed. In order to identify the most suitable mitigation

Table 1
Database distribution and search keywords used.

Category	A	B	C	D	E	F	G	H	I	J	K	L	M	Total	Keywords
The impact of climate change & built environment	2									6	1	1	1	11	Climate change, urban environment, built environment, building sector
Climate change impact on building energy demand	32	1			1						1			35	Climate change, building energy demand, heating demand, cooling demand
Climate change impact on building energy systems	12									5	1			18	Climate change, building system, district heating, district cooling, air-conditioning
Building renovation as a mitigation measure	50	1	1							9	1	1		63	Climate change, buildings, renovation, retrofitting, refurbishment
Policy & societal aspects of renovation	12	3	1	2		1	1	1	1		1		1	24	Climate change, building renovation, policy, society, optimization, efficiency, large-scale
Economic aspects of renovation	10	1												11	Climate change, building renovation, cost, cost effectiveness, economic
Environmental aspects of renovation	7													7	Climate change, building renovation, LCA, emergy, environmental, impact
Total														169	

A – Science Direct; B - Springer; C - Taylor & Francis; D - SAGE; E – MDPI; F – Wiley & Sons; G – Inderscience Publishers; H – Frontiers Media; I – Emerald Group Publishing; J – Governmental and environmental agencies; K – Conference proceedings; L – Academic theses; M-book chapter.

measure, the efficiency of different building renovation measures are reviewed and compared. Finally, challenges and obstacles for the large-scale implementation of such measures are discussed from the policy, economic and environmental standpoints.

2. Methods

Several literature sources were considered in order to collect and categorize the bibliography for this review. Primarily, peer-reviewed journal papers published in English were considered, published until April 2018. Several renowned (Science Direct, Taylor & Francis, Springer, SAGE, Wiley & Sons, Emerald Group Publishing) and emerging (MDPI, Frontiers Media) scientific databases were considered for the initial survey. Additional sources such as book chapters, academic thesis, conference proceedings, and reports from environmental and governmental agencies were also considered in order to improve the coverage of the research material available. In order to refine the search, based on the facts presented within the introductory section, seven categories were considered, as shown in Table 1 (categorized analogue to the methodology previously applied by Mannan et al. (2018)). In order to perform the search for each category, several keywords were used. Considering that two keywords were common for all categories (climate change, building), the literature was categorized based on the match of at least three keywords. After the initial categorization, final filters were applied. The studies that were addressing solely the heat island effect were disregarded from further considerations, due to the fact that the effect itself (higher outdoor temperatures in dense urban environments compared to rural environments) is rather a consequence of urbanization (building agglomeration and materials used for the construction) than the climate change itself. Duplicates were also removed: if the study was published in both the thesis/conference and one of the scientific databases in form of a journal paper, it was considered solely as a journal publication. It should be noted that Elsevier's Energy Procedia was treated as a journal in this study, and all conference proceedings published within the volumes available were treated as journal publications. The final selection included 140 journal papers, 20 governmental and environmental reports, 4 conference proceedings, 3 academic thesis and 2 book chapters, resulting in total of 169 studies reviewed.

3. The impacts of climate change on building energy demand & energy systems

3.1. The impacts on energy demand

The impacts of climate change on building energy demand were previously studied within the literature in multiple studies, which evaluated the current state of the observed building stock, and its energy performance under current and forecasted weather conditions (as given in Table 2). An initial overview of the impacts was elaborated upon in 2012 by de Wilde and Coley (2012). However, significant research efforts were published over the 2012–2018 period, which will be further summarized and analyzed within this subsection along with the papers published prior to 2012 in order to provide a detailed knowledge database to the reader. An overview of the impacts assessed is provided in Table 2, sorted by the case study location. Since the authors considered various time horizons, in order to enable a comparison of the impacts on a similar basis (or as close as possible), the results within the table are given for the year that was most common for the scenarios used—2050. However, in instances where the year 2050 was not considered, the impacts for the closest timeline are used for comparison (for example, if the study considered the years 2070 and 2100 within the scenarios, the results for 2070 are used within Table 2). Additionally, while some studies provided results in the form of heating and cooling demand, several studies used total building energy demand (which includes electricity consumption for lighting and appliances). However, several studies (Invidiata and Ghisi, 2016; Radhi, 2009; Shen, 2017a; Shibuya and Croxford, 2016; Wang et al., 2010) provided results in both forms, which will be addressed in detail later on within this subsection. For better clarity, within Table 2 and in further text, decrease in energy demand is denoted with a "–" prefix, while an increase is denoted with a "+" prefix.

The general assumption made by the authors of the reviewed studies was that during summer months, due to the increased outdoor temperatures, the difference between the indoor comfort set point temperature and outdoor temperature will increase, consequently increasing the energy demand for cooling. On the other hand, during the winter months, the difference between the indoor comfort set point temperature and outdoor temperature will decrease, reducing the energy demand for heating. The majority of the studies used CCWorldWeatherGen tool (developed at the University of Southampton) for developing weather scenarios. In order to predict future weather conditions, the tool requires two main inputs: output files from the Hadley Centre HadCM3 Global Circulation Model for the A2 family of IPPC (Intergovernmental Panel on Climate Change) scenarios and TMY (Typical Meteorological Year) for the study location. The assumption proved to be true in all studies reviewed, with the rate of increase/decrease varying depending on the climate conditions of the location studied. According to the results presented, buildings located in hot climates will have the most dramatic shift in heating/cooling demand ratio. For example, in the humid subtropical climate

Table 2
Overview of climate change impacts on building energy demand in different regions.

Study	Country	City	Reference period	Observed period	Heat demand decrease [%]○	Cooling demand increase [%]	Total building energy demand [%]
Australia							
Wang et al. (2010)	Australia	Alice Springs	1990	2050	−50 to-65	+62 to +84	+41 to +56
		Darwin			*	+39 to +57	+39 to +57
		Hobart			−19 to −28	+79 to +173	−19 to −26
		Melbourne			−30 to −42	+69 to +111	−16 to −20
		Sydney			−66 to −81	+93 to +146	+61 to +101
Guan Guan, 2009		Adelaide	2008	2070		+36	
		Brisbane				+35	
		Canberra				+40	
		Darwin				+45	
		Hobart				+29	
		Melbourne				+28	
		Pert				+31	
		Sydney				+59	
Guan (2012)		Adelaide	2011	2070			+9.8
		Brisbane					+11.7
		Canberra					+9.3
		Darwin					+15.1
		Hobart					+6.4
		Melbourne					+9.1
		Pert					+9.8
		Sydney					+11.6
Europe							
Waddicor et al. (2016)	Italy	Turin	2010	2050	−16	+30	
Nik and Sasic Kalagasidis, 2013	Sweden	Stockholm	2011	2081–2100	−25 to −30	+2 to +14	
Tettey et al. (2017)		Växjö	1961–1990	2050–2060	−22	+27	
Dodoo et al. (2014)		Växjö	1996–2005	2050	−13 to −16	+39 to +49	
Berger et al. (2014)	Austria	Vienna	1980–2008	2050	−11 to −30	+28 to +92	
Jylhä et al. (2015)	Finland	Vantaa	1980–2009	2050	−14 to −17	+28 to +34	
Andrić et al., 2016a,b	Portugal	Lisbon	2010	2050	−6.7 to −37.1		
Dolinar et al. (2010)	Slovenia	Ljubljana	2005	2050	−14 to 32	+56 to +916	
		Portoroz			−6	+61 to 102	–
Vidrih and Medved (2008)		Ljubljana	1992–2003	Not def.		+42 to +170	
Sabunas and Kanapickas (2017)	Lithuania	Kaunas	1990–1999	2080			+15 to +15.6%
Americas							
Shen (2017a)	United States	Philadelphia	1961–1990	2040–2069	−14.7 to −27.4	+27 to +35.2	−1.64 to −6
		Chicago			−16.4 to −28.5	+24.8 to +32.9	−4.3 to −9.4
		Phoenix			−35.4 to −48.9	+17.4 to 24.2	+4.9 to +6.9
		Miami			*[1]	+26.6 to +36.4	+14 to 19.5
Jiang et al. (2017)		Daytona	1991–2005	2050	−48	+36	
		Jacksonville			−46	+43	
		Key West			−68	+27	
		Miami			−79	+30	
		Orlando			−57	+35	
		Pensacola			−48	+41	
		Tallahassee			−50	+43	
		Tampa			−61	+35	
L. Wang et al. (2017a)		Miami	2006	2050			+6.5
		Phoenix					+8
		Los Angeles					+6
		Washington					+2
		Akron					+1
Angeles et al. (2017)	Cuba		2006–2020	2041–2060			+8.6
	Dominican Republic						+8.7
	Guatemala						+16.7
	Haiti						+8.9
	Panama						+8.1
	Puerto Rico						+8.2
	Trinidad & Tobago						+7.7
	Venezuela						+12.9
Invidiata and Ghisi (2016)	Brazil	Curitiba	2015	2050	−79	+210	+56
		Florianópolis			−82	+120	+112
		Belém			*	+70	+11
Asia							
Y. Wang et al. (2017)	China	Jinan	2020	2050		+30.7	

Table 2 (*continued*)

Study	Country	City	Reference period	Observed period	Heat demand decrease [%]○	Cooling demand increase [%]	Total building energy demand [%]
Xiang and Tian (2013)		Tianjin	1971–2010	2011–2050	−18.1		
Wan et al. (2011)		Harbin	1971–2000	2001–2100			−6.1
		Beijing					+1.9
		Shanghai					−3.4
		Kunming					+7.9
		Hong Kong					+7.6
Huang and Hwang (2016)	Taiwan	Taipei	2000–2010	2050	*	+59	–
Yau and Hasbi (2017)	Malaysia	Kuala Lumpur	2000	2050		+8	
Shibuya and Croxford (2016)	Japan	Sapporo	1990–1999	2040–2050	−27	+23	+3
		Tokyo			−263.6	+17	+13
		Naha			*	+9	+9
Radhi (2009)	United Arab Emirates	Al-Ain	2009	2050	−9.5 to −39.2	+7.3 to 24.1	+4.1 to +12.5
Roshan et al. (2012)	Iran		2005	2050	−14	+30	
Africa							
Ouedraogo et al. (2012)	Burkina Faso		2010–2029	2030–2049	*	+56	

[1]*heating or cooling demand was non-existent in the reference year.

(according to the Köppen climate classification) of Sydney, Australia, annual heat demand could decrease by up to −81%, while the cooling demand could increase to almost 150% (Wang et al., 2010). Other case studies for buildings located in humid subtropical climates have similar findings (Table 2): Invidiata and Ghisi (2016) and Jiang et al. (2017) estimate rates of −82/+120% and −79/+41% of heating/cooling demand decrease/increase for buildings located in Florianópolis (Brazil) and southern Florida (United States). On the other hand, the impact in colder climates are significantly lower: for the case studies of the Swedish building stock (Dodoo et al., 2014; Nik and Sasic Kalagasidis, 2013; Tettey et al., 2017), the average decrease/increase rate is −21/+26%. The most extreme decrease in heat demand of −264% (Shibuya and Croxford, 2016) for the timelines observed was noted for Tokyo (Japan), while the most extreme increase in cooling demand (+150%) was obtained by Wang et al. (2010) for Sydney (Australia).

However, it should be noted that decrease/increase rates are relative to the reference heating/cooling ratio of the building observed. In other words, a higher percentage decrease in heating demand than the percentage increase in cooling demand does not necessarily mean that the total building energy demand will decrease, and vice versa. For example, if the observed building has a significantly higher ratio of cooling in total building energy consumption, total building energy demand in the future will increase, even if the percentage reduction in heat demand is significantly higher than the percentage increase in cooling demand. This assumption is supported by the results of the case studies of Tokyo (Japan) by Shibuya and Croxford (2016) and Hobart (Australia) by Wang et al. (2010). In the case of Tokyo, total building energy demand in 2050 increased by approximately +13%, even after the decrease in heating demand of −263% and increase in cooling demand of approximately +17%. Such a result can be justified by the fact that for the reference weather conditions in Tokyo (which has a cooling-predominant, humid subtropical climate), heating demand had a share of only 5% of total building energy consumption, while space cooling was responsible for almost 95% of building energy use. Shen (2017a) had similar findings for the case study of Phoenix (Arizona, U.S.) with a hot desert climate—building energy demand increased by up to +7% after the −49% and +24% decrease/increase in heating/cooling demand, respectively. On the other hand, in Hobart (which has a mild temperate oceanic climate), total building energy demand decreased by up to −26%, even after the +173% increase in cooling demand and decrease in heating demand of just −28%.

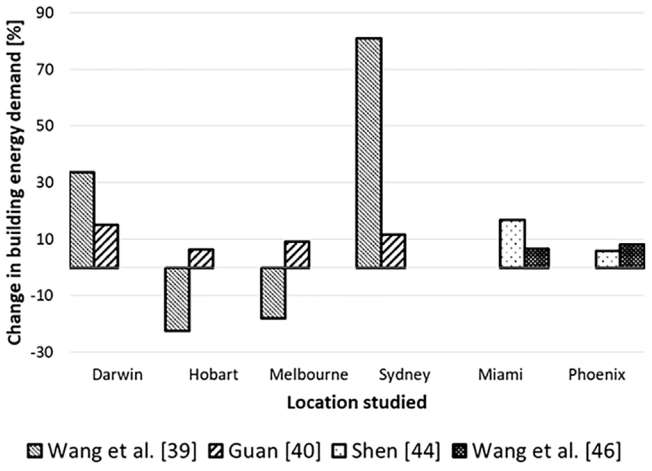

Fig. 2. Comparison of impacts obtained by the authors for the same locations.

It should be noted that the results obtained by different authors for the same case study location can vary (Fig. 2). For example, the increase rates in total building energy consumption for four Australian cities (Darwin, Hobart, Melbourne, and Sydney) that were featured in studies by both Wang et al. (2010) and Guan (2012) differed significantly. For example, the study by Guan suggested an increase in building energy demand of +11.6% in 2070 for buildings situated in Sydney, while the study by Wang et al. suggested an increase of approximately 80% (average value within a given range). Moreover, while in the study of Wang et al., building energy demand in the cases of Hobart and Melbourne decreased by approximately −22% and −18%, respectively, the results from Guan's study suggested an increase of approximately +6% and +9%, respectively. The results for Miami and Phoenix also differed between the studies by Shen (2017a) and L. Wang et al. (2017a), although less drastically—in the case of Miami, the difference was nine percentage points, while in the case of Phoenix, the difference was less than two percentage points.

Such variations in results between the two case studies for Australia can be explained by differences in the modeling approaches used and building types considered. The authors used different weather databases and climate models to create a representative meteorological year for a reference case and future weather scenarios (nine different global circulation models (GCMs)

and a morphing approach (Wang et al., 2010) vs. one GCM and an improved imposed offset method (Guan, 2012)), as well as different building energy modeling tools (AccuRate (Wang et al., 2010) vs. DOE-2.1E (Guan, 2012)). Furthermore, different building types (a four bedroom house (Wang et al., 2010) vs. a ten-story office building (Guan, 2012)) and forecast horizons (2050 (Wang et al., 2010) vs. 2070 (Guan, 2012)) were considered. On the other hand, studies by Shen (2017a) and L. Wang et al. (2017b) used the same climate and building modeling approaches (the morphing method developed by Jentsch et al. (2013, 2008)) and EnergyPlus, respectably), which can explain the less significant differences between the results obtained. However, the authors used different case study buildings: a low-raise residential building (Shen, 2017b) and a medium-size office building (L. Wang et al., 2017b). In order to understand such variations in results, all studies on the topic should clearly state sources of reference regarding weather data, building properties, and approaches used for climate and building energy modeling (as was the case in the four studies discussed within this paragraph). Furthermore, as the results suggest, the impacts should be presented for heating and cooling demand as well as for total building energy consumption in order to fully comprehend the impact scale. Moreover, based on the results presented, it is relevant to perform simulations for different building types in order to assess the impact on the built environment since the impact scale could vary between the types. Finally, it should be noted that considering the uncertainties related to climate change modeling, it is not expected that such studies will provide precise results and dictate policies, but rather provide future trends and guide them.

3.2. Implications for energy systems

3.2.1. Decentralized air-conditioning (AC) systems and power grids

The suggested shift in building energy demand could have long-term impacts on energy systems, especially in developing countries with hot climates, such as Arabian Gulf. In these countries, the majority of cooling services are provided by mechanical decentralized air-conditioning (AC) systems, which are the main consumers of electricity produced. It is a general estimation that in hot climate regions, up to 80% of total energy consumption can be attributed to mechanical cooling systems (Dabaieh et al., 2015). For example, air-conditioning in Kuwait accounts for 45% of total electricity consumption, and it is responsible for 70% of electricity peak demand (Ameer and Krarti, 2016). Even under the current climate conditions, Kuwait is facing challenges to meet the electricity demand over the summer months, experiencing frequent power outages and burnouts (Ameer and Krarti, 2016). The situation is similar in Egypt, where the building sector accounts for 42.3% of national energy consumption: over the course of 2012–2013, the deficit between the electricity demand and electricity generation was almost 9%, which resulted in frequent blackouts of 1–2 h per day (Dabaieh et al., 2015). Such stress on the grid will have multiple impacts. Primarily, from a social aspect, blackouts affect comfort and the everyday life of inhabitants. Secondarily, the current economy of such countries could be significantly impacted due to production and service downtimes. Namely, during the Kuwait power outrage in February of 2015, three oil refineries with capacities of 930,000 barrels per day were closed for one week, which had a significant impact on the national economy (Ameer and Krarti, 2016). Considering the predicted increase in cooling demand, these outbreaks could become more frequent and last longer. However, even if the current power system is upgraded to cover the predicted increase in cooling demand, the surge in consumption could still hurt the economy. For example, considering that the electricity in Kuwait is generated by oil, and that the economy of Kuwait is largely based on oil exports (87% of all exports), an increase in local consumption would lower the exports and consequently the country's main revenue stream. The study by Ameer and Krarti (2016) suggested that as of early 2017, almost 20% of Kuwait's national oil production is used in order to cover the local electricity demand. The findings of Alaidroos and Krarti (2015) suggest an analogue scenario for the KSA. Finally, an increase in cooling demand in these countries could increase the environmental impact of the energy systems. Since their electricity production is largely based on fossil fuel consumption, an increase in electricity production would also significantly increase their already substantial carbon footprint, and have a major impact on air, land, and water quality (Alaidroos and Krarti, 2015; Alnatheer, 2006). Potential solutions for this problem would be an increase in renewable and clean energy production and energy efficiency implementations. However, despite the abundance in resources for renewable electricity production in these countries (solar radiation and marine territory for offshore wind farms), the use of such sustainable technologies such as solar plants and wind farms is exceptionally rare (Taleb and Sharples, 2011), mainly due to the fact that they are not considered to be financially feasible as fossil fuel cost is very low. However, due to the recent climate change accords and plummeting oil prices, these countries are investing significant effort in order to move from an oil-based economy to a more sustainable one, which could result in an increase in renewable energy systems' participation in energy production.

3.2.2. District heating systems

In developed regions with a cold and temperate climates, such as continental Europe, the shift in both heating and cooling demand could have an impact on urban energy systems. In developed and dense urban environments, heating services are provided by district heating systems, where heat is produced centrally in a heat plant and then distributed via underground networks to consumers. The benefits of such systems are numerous: heat production in high-capacity units situated outside the dense urban environment, the potential for the use of various renewable heat sources (solar, geothermal, etc.) and waste heat, improved overall environmental and economic efficiency, comfort and security of supply, as well as lower heating prices for consumers. Due to such benefits, the expansion of existing and the construction of new district heating systems has been widely proposed within environmental (Andrić et al., 2016b; Lake et al., 2017), economic (Gils et al., 2013; Grundahl et al., 2016; Ziemele et al., 2015) research studies and reports from environmental agencies (Connolly et al., 2012; Dolman et al., 2012) and governmental bodies (European Comission, 2012; European Parliament, 2016; The Scottish Government, 2014). However, significant investments are required in order to construct and enable the operation of district heating systems. The initial investments are returned through heat sales over a relatively long investment return period. Thus, the feasibility of such systems is highly dependent on heat sales (i.e., heat demand). Considering the heat demand decrease rates presented within Table 2, the investment return period could increase, impacting the feasibility of such systems. For example, the studies of cities located in Sweden (Dodoo et al., 2014; Nik and Sasic Kalagasidis, 2013; Tettey et al., 2017), where district heating systems cover 40–60% of demand (Swedish Energy Agency (Energimyndigheten), 2012), concluded that heat demand could decrease by up to −30%, consequently reducing the district heat demand density (the ratio between total annual district heat demand and overall surface of the district), which is one of the main parameters for the feasibility assessment of district heating systems. Additionally, reduced heat demand could significantly impact the operational parameters of the system. Usually, heat production

units in such systems are designed so that approximately 75% of demand is covered by a base load unit and 25% by a peak load unit. Due to the heat demand reduction of over −50%, required production would be below the technical minimum of a base load unit, which would mean that most of the demand would be covered by peak load units that commonly use fossil fuels. Consequently, prolonged operation of peak load units would increase operational costs and CO_2 emissions. This aspect is crucial taking into account that incentives and subsidies for such systems are usually granted based on the utilization of renewable energy sources in energy production. Moreover, a reduced number of heat demand hours over the heating season would consequently result in continuous starts and stops in production, which would further reduce the efficiency of the overall system and increase the costs. However, the impact could vary between different climates suitable for heating services (Andrić et al., 2017a), depending on the demand decrease rate (Table 2). In more severe climates, heat production units would be operating with reduced capacity, while the number of operational hours (i.e., hours with heat demand) would remain almost unchanged. Contrarily, in milder climates, both the required capacity and number of operational hours would decrease. However, it should be mentioned that the feasibility values of district heat demand density are based on currently available technologies, their limitations and prices, and could consequently fluctuate in the future (especially since in certain countries, district heating systems are eligible for substantial subsidies).

3.2.3. District cooling systems

District cooling systems are analogue to district heating systems: they distribute cooling capacity in the form of chilled water or some other medium from a central source to an urban environment through a network of underground pipes (Energyland, 2018). While these systems share the same social, economic, and environmental benefits as district heating systems, the number of cooling systems in operation is significantly lower (according to Werner (2017), district heating systems cover approximately 11.5 EJ of heat demand across the E.U., U.S., and northern Asia, while district cooling systems cover up to 300 PJ of cooling demand: approximately 200 PJ is in the GCC region and 80 PJ is in the U.S.). The systems installed have a relatively high capacity—for example, the network located in Doha (Qatar) and operated by Qatar Cool is currently the system with the largest capacity installed (450 MW), with an additional 1760 MW planned for the Lusail City Project. However, up to a ten-fold increase in cooling demand (Table 2) would result in a significant strain on the production units within the existing district cooling systems, which were designed based on the reference demand. Both base load and peak load units would be under significant strain and would become eventually insufficient, since both the demand and the number of hours with cooling demand could increase significantly.

In contrast to the case with heat demand and heating hours in heating-dominated climates, it is expected that in cooling-dominated climates, the number of hours with cooling demand will increase in all climate subtypes, as it can be seen in Table 2 (with the increase rate variation based on the reference climate conditions). The most obvious solution would be the installation of additional cooling units—however, new units require additional investment costs, which would consequently prolong the investment return period for such systems. In order to retain the feasibility of such systems, district cooling utilities would be forced to increase the price of cooling services, which could cause customer disconnections from the system. Aside from the improved comfort for which customers decide to connect to district cooling systems in the first place, another reason that attracts customers is the relatively stable prices. If prices increase, customers may decide to shift towards some of the competitive decentralized technologies, such as heat pumps. These systems might present initial financial burdens to customers compared to the district cooling system connection, but they could realize the long-term profitability (due to the lower operational costs). On the other hand, for the district cooling systems in the design phase, increased demand in the future would mean increased district cooling demand density and improved feasibility (if the production units are designed to cover future demand rather than the reference one).

4. The efficiency of building renovations as a mitigation measure

As discussed within the introductory section, building renovations are currently the most commonly proposed measure for the mitigation of changed building energy patterns and reduction of building sector-related emissions. Building renovation measures can be divided into three main categories: passive, active, and additional measures as summarized in Table 3.

Passive renovation measures include the application of additional insulation layers, improving the envelope air-tightness, installation of energy-efficient glazing, the addition of solar-shading devices and overhangs, installation of green roofs/walls, natural ventilation/night cooling, and changing the solar reflectivity and/or absorptivity of building envelope surfaces. The application of additional insulation layers improves the heat transfer coefficient (U-value) of the envelope elements (walls, roofs, floors),

Table 3
An overview of building renovation measures.

Building renovation measures	
Conventional measures	
Passive measures	*Active measures*
Additional insulation	Solar panels (PV panels and solar collectors)
Improved air-tightness of the envelope	Heat pumps
Energy efficient glazing	Connection to district heating/cooling
Solar shading devices/overhangs	Energy efficient lighting
Green roofs/walls	Energy efficient appliances
Natural ventilation/night cooling	Sophisticated control devices
Solar reflectivity/absorptivity	
Additional measures	
Thermal mass	
Windows-to-wall ratio	
Indoor comfort temperatures	

which reduces the rate of heat transfer between the building's indoor and outdoor environment (and thus reduces heating and cooling demand). The current available and most commonly used envelope insulation materials are expanded (EPS) and extruded (XPS) polystyrene, polyurethane, and glass wool, while emerging materials and technologies include aerogels, phase-change materials, gas-filled panels, and vacuum insulation panels (Xing et al., 2011). Improving the air-tightness of buildings by sealing cracks, interstices, or other unintentional openings in building envelopes reduces the uncontrolled inward and outward leakage of air caused by the pressure effects of wind and/or the stack effect (Limb, 1992). In order to reduce the air infiltration rate, these cracks and openings are either covered by polyethylene tape (Co2olBricks, 2013) or filled with silicone or mineral wool (Gillott et al., 2016). Installation of energy-efficient glazing such as double-pane windows (argon-filled and/or tinted) reduces solar gains and heat transfer. New glazing technologies, such as electrochromic glazing (electronically tintable glazing, whose solar properties can adapt to the variation of solar radiation while remaining transparent) are also expected to reach market maturity (Paule et al., 2017) and could be used as a renovation measure in the upcoming years. Adding vegetation layers on walls and roofs reduces the surface temperature of envelopes (and consequently, energy use for cooling) due to the shading and evapotranspirative effect of the plants (Charoenkit and Yiemwattana, 2016; Pérez et al., 2011a). Natural ventilation (wind driven ventilation and/or buoyancy-driven ventilation) is the process of supplying or removing air from the indoor environment by natural means, without the use of a mechanical system (Al-Sanea et al., 2012). Night cooling refers to the operation of natural ventilation at night in order to remove excess heat and reduce indoor temperatures. By covering building envelope surfaces with a coating that has high solar reflectivity and low solar absorbance, the amount of solar radiation absorbed by the surface is lowered, resulting in decreased solar gains and surface temperatures.

On the other hand, through the active measures, a building's carbon footprint is reduced by utilizing renewable energy sources in order to cover the building's energy demand. These measures include the installation of PV and solar thermal panels in order to fully or partially cover building electricity and space heating/domestic hot water demand, respectively; heat pumps and connections to district heating/cooling networks for heating/cooling services; and the installation of energy-efficient lighting and appliances with sophisticated control devices in order to reduce internal heat gains and electricity consumption. Additional considerations could include changes to the thermal mass of the envelopes and window-to-wall ratio (WWR, increase or decrease of overall glazing surface) and changes in the comfort set point temperatures. Considering that modifications to thermal mass and WWR require changes to a building's structure (and require more pre-construction than post-construction strategy), and that changing the set point temperature can be considered more as a behavioral measure, it is the opinion of the authors that they should be considered as a separate category. The efficiency of passive (wall insulation ((Abdelrahman and Ahmad, 1991; Bolattürk, 2006; Kharseh and Al-Khawaja, 2016; Sadineni et al., 2011; Taleb and Sharples, 2011), thermal mass (Al-Sanea et al., 2012; Al-Sanea and Zedan, 2011), shading devices (Aldawoud, 2013), green walls (Charoenkit and Yiemwattana, 2016), reflective roofs (Mohamed et al., 2015) and active (appliances and efficient lighting (Ameer and Krarti, 2016; Harvey, 2009; Taleb, 2014)) renovation measures under current climate conditions has been previously debated within the literature. However, considering the scope of this study, only studies that considered the performance of renovation measures under future weather conditions will be discussed within this section (Table 4). It should also be noted that in order to evaluate the efficiency of renovation measures as a climate change mitigation measure rather than just building energy saving measure, a life-cycle analysis should be performed in order to assess the balance between the impact of renovation material/equipment production/recycling and energy savings achieved, which will be addressed in detail in section 5.3 of this study.

4.1. The efficiency of passive renovation measures

In a study of residential buildings in the UAE, Radhi (2009) found that under future climate conditions, reducing the U-value of the envelopes by applying additional insulation levels could reduce heating and cooling demand by −23% and −20%, respectively. Consequently, total building energy demand decreased by up to −15.9% (due to the fact that the ratio of heating and cooling in total energy consumption was 93/7%). Other studies that addressed the performance of renovated residential buildings in locations with hot and humid climates (Brazil and Taiwan) had similar findings. In a case study of cities in Brazil (Invidiata and Ghisi, 2016), the authors concluded that improving envelope insulation could decrease total building energy demand by up to −27%, while Huang and Hwang (2016) found that such a renovation measure could achieve approximately −42% savings in cooling demand under the climate conditions characteristic for Taiwan. A significant reduction in heat demand (up to −57%) could also be achieved in temperate climates by applying thermal insulation to residential buildings, as was found in a case study of the Netherlands (Van Hooff et al., 2016). On the other hand, in the studies of residential buildings located in colder climates, such as the one in Sweden, the reduction in heat demand was significantly lower (less than −15% for all three case study locations considered: Stockholm, Gothenburg, and Lund (Nik et al., 2016, 2015)).

The installation of energy-efficient windows proved to be an efficient measure for reducing both heating and cooling demand in all climate types considered, ranging from approximately −9% to −17% for heating demand, and −3% to −6% for cooling demand. The combination of these two measures (envelope thermal insulation and energy-efficient glazing) proved to be the most efficient solution for reducing residential building heat demand in various climate types—up to −87% (Andrić et al., 2018, 2017a; 2016a). In a case study of office buildings in Japan, the impact of such a combination of measures on total building energy demand was less significant: −8% in the heating-dominated city of Sapporo and −3% in the cooling-dominated city of Naha (according to the figures provided by the authors of the study). However, the result for Tokyo, which has a cooling-dominated climate, was in contrast—total building energy demand increased after the application of additional insulation measures and the installation of energy-efficient glazing. The authors of the study did not discuss this particular result, but it can be assumed that an increase in total energy consumption was caused by overheating during summer months due to increased insulation levels.

The effect of solar -shading devices/overhangs differed between the studies. In the case studies of residential buildings in the climate conditions found in Brazil (Invidiata and Ghisi, 2016), Taiwan (Huang and Hwang, 2016), Netherlands (Van Hooff et al., 2016), and Sweden (Tettey et al., 2017), as well as office buildings in Burkina Faso (Ouedraogo et al., 2012), limiting the amount of solar radiation that reaches the buildings' walls significantly reduced cooling demand (by approximately −30% to −90%). On the other hand, in case studies of residential buildings in the UAE (Radhi, 2009) and office buildings in Japan (Shibuya and Croxford, 2016), reduction in cooling demand was significantly lower (less than −10% in all instances). However, in most studies, the application of solar-shading devices and overhangs increased building heat demand due to the fact that solar gains were

Table 4
The effect of mitigation measures under future weather conditions.

Study	Country	City	Horizon	Renovation measure	Effect [%]		
					Heating demand	*Cooling demand*	*Total building energy demand*
Radhi (2009)	UAE	Al-Ain	2050	Thermal insulation	−23.8	−19.7	−15.9
				Thermal mass (+)[a]	−26.4	−12.6	−11.2
				Solar shading devices	−3.3	−3.4	−2.8
				Energy efficient glazing	−9.4	−5.5	- 4.7
				Windows-to-wall-ratio (+)	+16.4	+8.4	+7.4
Nik et al. (2015)	Sweden	Gothenburg	2041 −2060	Thermal insulation	−7.1 to −10.2		
				Energy efficient glazing	−16.6		
Nik et al. (2016)	Sweden	Stockholm	2041 −2060	Thermal insulation	−7 to −13.9		
				Energy efficient glazing	−14.7		
				Energy efficient lighting	+5		
				Energy efficient appliances	+13		
				Indoor comfort temperature	−27.6		
		Gothenburg		Thermal insulation	−8.3 to −12.5		
				Energy efficient glazing	−17.1		
				Energy efficient lighting	+5.6		
				Energy efficient appliances	+14.4		
				Indoor comfort temperature	−30.7		
		Lund		Thermal insulation	−8.2 to −14.7		
				Energy efficient glazing	−11.9		
				Energy efficient lighting	+5.8		
				Energy efficient appliances	+14.6		
				Indoor comfort temperature	−32.3		
Tettey et al. (2017)	Sweden	Växjö	2050	Energy efficient appliances	+20	−40	−35
				Solar shading	+22	−91	−38
Andrić et al., 2016a,b	Portugal	Lisbon	2050	Thermal insulation + efficient glazing	−22.3 to −52.4		
Andrić et al. (2018)	France	Nantes	2050	Thermal insulation + efficient glazing	−73		
Van Hooff et al., 2016	Netherlands	De Bilt	Generic[b]	Thermal insulation	−57		−4 to −7
				Thermal mass (−)	−1 to −2	+16	+4
				Roof reflectivity	−1 to −2	−10	< −1
				Solar shading devices	+1	−74	−6
				Green roof	−2	−3	−2
				Natural ventilation		−59	−5
Huang and Hwang (2016)	Taiwan	Taipei	2050	Thermal insulation		−31.3 to −42.3	
				Solar shading devices		−37.5	
Shibuya and Croxford (2016)	Japan	Sapporo	2040 −2050	Thermal insulation + efficient glazing			−8
				Energy efficient lighting			−3
				Indoor comfort temperature			−17
				Solar shading devices			+3
				Night cooling			−10
		Tokyo		Thermal insulation + efficient glazing			+2
				Energy efficient lighting			−23
				Indoor comfort temperature			−1
				Solar shading devices			+15
				Night cooling			+9
		Naha		Thermal insulation + efficient glazing			−3
				Energy efficient lighting			−18
				Indoor comfort temperature			+2
				Solar shading devices			+10
				Night cooling			+5
Andrić et al., 2017a,b	Canada	Resolute	2050	Thermal insulation + efficient glazing	−72 to −76		
	Canada	Yellowknife		Thermal insulation + efficient glazing	−72 to −76		
	Germany	Hamburg		Thermal insulation + efficient glazing	−77 to −82		
	Italy	Milan		Thermal insulation + efficient glazing	−77 to 83		
	Spain	Madrid		Thermal insulation + efficient glazing	−81 to −87		
Invidiata and Ghisi (2016)	Brazil	Curitiba	2050	Thermal insulation			−27

(*continued on next page*)

Table 4 (*continued*)

Study	Country	City	Horizon	Renovation measure	Effect [%]		
					Heating demand	*Cooling demand*	*Total building energy demand*
				Solar absorbance			−31
				Solar shading devices			−13
		Florianopolis		Thermal insulation			−17
				Solar absorbance			−22
				Solar shading devices			−9
		Belem		Thermal insulation			−27
				Solar absorbance			−12
				Solar shading devices			−38
				Windows-to-wall-ratio			−38
Ouedraogo et al. (2012)	Burkina Faso		2030 −2049	Thermal insulation		−8	
				Thermal mass (+)		+3	
				Energy efficient glazing		−3.4	
				Solar shading devices		−40	
				Windows-to-wall ratio (−)		−31	
Guan (2012)	Australia	Adelaide	2070	Windows-to-wall ratio (−)			−2.46
		Brisbane		Windows-to-wall ratio (−)			−3.20
		Canberra		Windows-to-wall ratio (−)			−1.83
		Darwin		Windows-to-wall ratio (−)			−3.20
		Hobart		Windows-to-wall ratio (−)			−1.24
		Melbourne		Windows-to-wall ratio (−)			−1.85
		Perth		Windows-to-wall ratio (−)			−3.06
		Sydney		Windows-to-wall ratio (−)			−2.53

[a] The suffix (+)/(−) suggest that the characteristic was increased/decreased.
[b] The authors used weather data from 2006 for future weather scenarios because 2006 was significantly warmer than average, with frequent heat waves.

reduced (consequently, more heat was required to reach indoor comfort conditions).

Night cooling was addressed as a measure solely in the study by Shibuya and Croxford (2016), and the results indicated a decrease in total building energy demand of approximately −10% for office buildings in heating-dominated Sapporo, while interestingly, energy load in cooling-dominated Tokyo and Naha slightly increased. On the other hand, Van Hooff et al. (2016) concluded that natural ventilation could significantly reduce the cooling load for residential buildings in the Netherlands (up to −60%). According to the studies reviewed, increasing the solar reflectivity of roofs could decrease cooling demand by approximately −10% (Van Hooff et al., 2016), while lowering the solar absorptivity of walls could decrease total building energy demand by up to −30% (Invidiata and Ghisi, 2016).

Green roofs were considered as a renovation measure in only one of the studies reviewed. The study (Van Hooff et al., 2016) found that adding vegetation to roof structures could reduce heating and cooling demand by −2% and −3% (respectively) under the forecasted weather conditions for the Netherlands. However, the case study was focused on heating-dominated climates, while green roofs are expected to have the highest effect in cooling-dominated climates. Additionally, it is expected that the effect of green walls on building energy consumption will be significantly higher than the effect of green roofs due to the larger surface available. In other words, green walls have a greater potential than green roofs considering that within urban centers, the extent of façade greening can be double the ground footprint of buildings (Manso and Castro-Gomes, 2015). Moreover, green walls have multiple additional benefits, such as: improved urban biodiversity, storm water management and air quality; mitigation of the heat island effect; improved health and wellbeing of the residents; improved acoustic protection, image and increased property value (Manso and Castro-Gomes, 2015). However, the performance of green walls as a mitigation measure under future weather conditions was not considered in the studies currently available within the literature. According to the experimental (Cameron et al., 2014; Chen et al., 2013; Cheng et al., 2010; Hoelscher et al., 2016; Jim and He, 2011; Mazzali et al., 2013; Olivieri et al., 2014; Pérez et al., 2011a, 2011b; Perini et al., 2011, 2017; Wong et al., 2010; Yin et al., 2017) and modeling (Malys et al., 2016, 2014) studies, under current climate conditions, the application of green walls has promising results, reducing building energy demand in warm temperate and arid climates within a range of −5% to −50%, with the most common reduction rate varying between −20% and −30% (Pérez et al., 2014). However, one modeling study (McPherson et al., 1988) that addressed the shading effect of vegetation on residential building energy consumption (under the weather conditions of four U.S. cities (Madison, Salt Lake City, Tucson, and Miami)), suggested that heat demand could increase by up to +21% due to lowered solar gains. Nonetheless, while other renovation measures have been widely accepted, policy makers and energy efficiency agencies are still reluctant to endorse the use of green walls simply due to the lack of replicated data sets (Cameron et al., 2014). Currently, assessing the energy performance of buildings with integrated green walls under future weather conditions presents a challenging task due to the fact that the thermal simulation of green walls is not readily available within the commercial BIM (Building Information Model) software packages. For the previously mentioned modeling studies, the authors either developed their own model (either completely (Kontoleon and Eumorfopoulou, 2010; Malys et al., 2014; Susorova et al., 2013) or in the form of an EnergyPlus software plug-in (Dahanayake and Chow, 2017)), or used plug-ins already available for the simulation of vegetative roofs (such as the RoofVegetation model in the EnergyPlus software package) in order to model the performance of green walls (Carlos, 2015; Fantozzi et al., 2014; Griffonni et al., 2016; Lassandro and Di Turi, 2017). Thus, according to the current literature, additional research efforts should be invested in experimental studies of green wall performance in cooling-dominated hot climates, as well as in simulation model development in order to assess their performance under future climate conditions.

4.2. The efficiency of active renovation measures

As discussed previously, the installation of renewable energy systems reduces or completely mitigates the emission levels of

renovated buildings (in the case that total building energy demand is fully covered by such systems). Currently, there are several systems available, such as solar photovoltaic panels for electricity production, solar thermal collectors for heat and domestic hot water production, and heat pumps that can utilize various renewable sources (such as air, geothermal energy, etc.) in order to cover heating and cooling demand. As an alternative to such systems, connection to district energy systems with centralized energy production from renewable sources can be considered (for example, several solar-powered district heating systems have already been implemented in Denmark). Moreover, it is expected that the next generation of district energy systems will integrate a synergy between centralized and decentralized renewable energy systems (Lund et al., 2014). However, from all the studies reviewed, only one study (Andrić et al., 2018) considered renewable energy systems as part of the renovation package and evaluated its performance under future weather conditions. The results for the residential building stock considered (St. Félix district, located in Nantes, France) indicated that under future weather conditions and after the application of passive renovation measures (thermal insulation + energy-efficient windows), the annual heat production of solar thermal collectors will exceed the annual space heating and domestic hot water demand (assuming that all the available roof space is utilized for the installation of collectors). Nonetheless, after conducting the analysis on an hourly basis, the authors noted that heat production rate does not always match the heat demand rate. Namely, solar collectors have the highest output during summer months (when only domestic hot water heat demand exists), while during the winter, significant heat demand occurs during the nighttime when there is no solar radiation available. Thus, it was noted that in order to optimize energy demand and energy production, thermal storages with sufficient seasonal capacities should be installed in such cases.

The use of energy-efficient appliances in residential buildings situated in cold climates could reduce the internal heat load, increasing the heat demand by +20% and decreasing the cooling demand by −40% (Tettey et al., 2017), while their use in hot and humid climates could decrease total building energy demand by up to −23% (Shibuya and Croxford, 2016). According to the studies by Nik et al. (2016) and Shibuya and Croxford (2016), changing the indoor comfort set point temperatures (lowering the set point temperature during the heating season and increasing the set point temperature during the cooling season) could result in significant energy savings (up to a −23% decrease in heating and cooling demand). The application of smart control devices (that can adapt heating and cooling systems' operation according to the real-time occupancy and user behavior) was not considered within the studies reviewed. Considering that these technologies are readily available on the market (such as the Nest smart thermostat), it is the belief of the authors that they should be included in future considerations.

4.3. The efficiency of additional renovation measures

Considering thermal mass modification as a renovation measure, Radhi (2009) found that increasing building thermal mass could decrease heating and cooling demand by −26.4% and −12.6%, respectively, which is in accordance with the findings of Van Hooff et al. (2016) that a reduction in thermal mass resulted in an increase cooling demand (+16%). Such behavior was justified (in both studies) by the fact that an increased wall thickness enables building mass to store more heat for longer periods of time. However, the study by Ouedraogo et al. (2012) had a contrasting conclusion. Although the authors started with the same assumption, the results indicated that enhanced thermal mass caused an increase in cooling demand. The authors suggested that such behavior might be caused by the fact that during nighttime, the rate of heat release from the building envelope to the indoor environment is reduced due to the very large time constant but relatively low rate of nighttime ventilation (Ouedraogo et al., 2012). In other words, the envelope maintains a high internal temperature overnight, increasing the cooling load during the following day.

As for the window-to-wall ratio, the studies by Guan (2012) and Ouedraogo et al. (2012) indicated that lowering the percentage of glazing in office buildings would decrease the amount of solar gains and thus cooling demand (−2% to −30%). Interestingly, the results of Radhi (2009) suggested an increase in heating demand upon the increase of glazing area. Traditionally, with the increase of glazing area, solar heat gains also increase, reducing the amount of heating required in order to reach the indoor comfort temperature. However, if the majority of heat demand occurs during nighttime, heat demand could increase since the area of glazing, which has a higher U-value than the wall (and thus thermal transmittance) is increased while the wall area is reduced (thus, the rate of heat exchange between the outdoor and indoor environment is increased).

5. The implementation of building renovation measures: challenges and considerations

As discussed within the introductory section, in order to achieve the ambitious energy reduction goals already set for the building sector in developed countries, hundreds of thousands of buildings should be renovated each year. By ratifying the 2010/31/EU (European Parliament, 2010) and 2012/27/EU (European Parliament, 2012) directives for building energy performance and energy efficiency, respectively, the E.U. became a global leader in large-scale building renovation projects, requiring that all member states develop energy codes and renovation plans for their building stock. However, as indicated in the case study of the U.K., the actual renovation rate was less than 0.16% of the envisioned rate (less than 1000 homes were renovated per year out of the 600,000 planned). In order to identify what is hindering the renovation process, different aspects of large-scale renovations are discussed within this section.

As suggested by Mosgaard and Maneschi (2016), extensive energy renovations can be observed as a complex innovation process, defined by Van de ven et al. (2008), but contextualized in the framework of building renovations (Fig. 3). The first phase of the process is the *initiation*, whereby the building owner/tenant realizes (based on the new regulations, reports from energy efficiency agencies, media, or peers) that a building renovation is a possibility and/or necessity. During the *development* process, the building

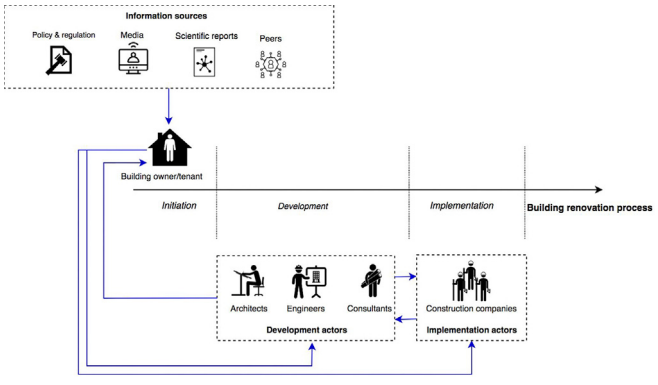

Fig. 3. Building renovation as innovation process (according to Mosgaard and Maneschi (2016)).

owner/tenant engages with different actors and stakeholders (engineers, architects, consultants, etc.) in order to find and analyze a potential solution for achieving the energy reduction goal set. Finally, within the *implementation* phase, the renovation measure is installed and put into operation. During these three phases, the building owner usually faces multiple obstacles caused by the aspects commonly overseen in policy frameworks—lack of information and a complex relationship between the stakeholders involved, and economic as well as environmental challenges.

5.1. Policy framework

In developed countries, despite over 20 years of building energy efficiency legislation, the legislative context has remained weak for the existing building stock (relative to the legislation framework for new buildings) (Building performance Institute Europe, 2014). The initial obstacle could be the unappropriated downscaling of polices. For example, the report from BPIE (Buildings Performance Institute Europe) (Building performance Institute Europe, 2014) evaluated the national renovation policies of ten EU member states, and found that on average, they were less than 60% compliant with the requirements of the 2010/31/EU directive. The report also found that national strategies lacked the required level of ambition, sense of urgency, and strategic importance. In one empirical study that included surveys of five member states (Beillan et al., 2011), the findings indicated that the main barriers (according to the building owners) in building renovations were a lack of information on potential measures and efficient savings; high costs; lack of incentives; and constantly changing, vague policies (Fawcett et al., 2011). According to Kvellheim (2017), ambivalent policies are common to new technological developments, considering that they support niche innovation that departs from stable structure—in this case, renovation technologies (energy-efficient envelope materials and renewable energy systems) can be considered as niche innovation compared to the technologies used for the construction of the existing building stock. History has shown that ambivalent policies create insecurity and can misguide the targeted sector, causing delays. Moreover, it is likely that political sectorial responsibility contributes to the ambiguity since different ministries operate in different areas, and are usually careful not to interfere with the responsibility of others (Kvellheim, 2017).

Usually, in order to achieve clarity and avoid confusion in the targeted sector, polices try to incorporate a universal model with a "one-size-fits-all" approach. In the case of the building sector, incorporating such a model is rather difficult due to the diversity of the housing stock (Karvonen, 2013; Palm and Reindl, 2016). Thus, extensive renovations should encompass different technologies rather than individual ones. Moreover, as discussed in Table 4 and Section 3 of this study, significantly higher energy savings are achieved through a combination of renovation technologies, rather than using a single one. Additionally, the current dominant model of renovation suggests a one-off renovation that immediately reaches the required energy performance. Instead, an alternative model could be used where the renovation is carried out over a longer period of time (Fawcett et al., 2011).

In order to define an appropriate combination of renovation measures for different segments of the building stock, detailed knowledge about the stock properties is required (Hrabovszky-Horváth et al., 2013; Korytarova, 2010; Novikova, 2008), with the most relevant being building geometry and envelope thermal properties. Nonetheless, collecting and aggregating reliable building data has proved to be a challenging task for policy makers and urban developers (Caputo and Pasetti, 2017; Hrabovszky-Horváth et al., 2013), usually caused by a lack of compulsive requirements and coordination between different scales municipal, national) of data collection (Caputo and Pasetti, 2017). While thermal properties can be assigned based on the building construction period (i.e., common construction materials used within that period), collecting building geometry data presents a challenging task. However, over the last decade, significant progress has been made with the breakthrough in techniques, such as the use of satellite and LiDAR (Light Detection and Ranging) imaging and the use of GIS (Geographic Information System) software, as in the studies by Caputo and Pasetti (2017), Johansson et al. (2017), Geiβ et al. (2011), Gils (2012) and Santos et al. (2014). Yet, the estimation of building energy consumption based on assumptions and collected data tends to consistently underestimate current energy consumption levels, potentially overestimating savings achieved by renovation measures (Moezzi and Janda, 2014; Sunikka-Blank and Galvin, 2012). Additionally, Moezzi and Janda (2014) suggested that policy frameworks assume mechanistic and even unrealistic behavior of building owners/tenants in regard to the manner in which they consume energy, and reasons why they would agree to change that behavior. This is why energy efficiency policies, implementation roadmaps and enforcement mechanisms should be developed by relevant stakeholders considering the local context rather than barrowing even the best practices from somewhere else.

The complexity and opaqueness of relationships between the actors and stakeholders involved (Fig. 3) also has an influence on renovation process efficiency. The findings of empirical studies (Nair et al., 2017; Palm and Reindl, 2016) that closely followed the renovation process for several residential buildings in Sweden and conducted a series of interviews with all actors involved found that it is quite difficult to coordinate the actors, increasing the challenge for the close cooperation required in order to incorporate adequate energy-efficiency measures. After attending multiple meetings between actors and stakeholders, Palm and Reindl (2016) concluded that there was a lack of a common goal, and that all participants had individual tasks. Moreover, based on the evaluation of the decision-making process during the building renovations (Kamari et al., 2017), it was found that there was a lack of system-thinking, and that new thinking approaches should be developed in order to identify and illustrate awareness and priorities among the stakeholders involved. Based on an empirical study conducted during the renovation process of a hotel in Denmark, Mosgaard and Maneschi (2016) concluded that trust between the actors involved is of utter importance. However, Abreu et al. (2017) found (based on a series of interviews with house owners in Portugal) that due to the high level of trust between the house owners and construction companies/craftsmen, energy consultants and architects were commonly left out of the renovation process. As a consequence, some buildings might not be renovated to the level required by the energy codes since the companies/craftsmen focused on traditional building technologies. Thus, for an optimal renovation process, close cooperation, trust, and communication between all actors and stakeholders involved is required. Moreover, it is also important to account for the cultural background, level of knowledge, and daily routines of the house owners/tenants, considering that these factors influence their choice of renovation measures (Abreu et al., 2017; Palm and Reindl, 2016). It should also be mentioned that anticipated challenges such as potential conflicts between house owners/tenants and neighbors due to building alterations, stress, and disruption to everyday activities during the renovation process should be taken into account (Jakob, 2010; Nair et al., 2017; Weiss et al., 2012). Moreover, co-benefits from renovations such as higher comfort levels, improved living conditions, and positive health effects should be highlighted to the house owners/tenants in order to facilitate the renovation process (Farsi, 2010; Klockner and Nayum, 2016; Organ et al., 2013; Weiss et al., 2012; Zundel and Stieβ, 2011).

On the other hand, in GCC countries, the thermal performance and energy consumption of the building sector were initially neglected by local energy authorities, and as a consequence, a lack of energy-efficiency standards and regulations have dramatically increased energy consumption by the sector over the last decade (Kharseh and Al-Khawaja, 2016). Currently, there are only a few studies available within the existing literature that consider the policy framework aspect of building renovations in GCC countries, but the findings indicate that these countries could face additional challenges in implementing and enforcing such measures. Energy generation in these countries is purely fossil-fuel based, and the availability of abundant oil reserves and heavily subsidized electricity created a lack of environmental awareness and sustainable construction policies (Al-Yami and Prince, 2006; Taleb and Sharples, 2011). For example, the study by Kharseh and Al-Khawaja (2016) found that in Qatar, the indoor set point comfort temperature in public and residential buildings is commonly set to 18 °C. However, in recent years, significant efforts have been made in order to create building energy codes and reduce building energy consumption. While the current absence of policies presents an urgent need and significant opportunity to reduce building energy consumption in the future, new policies should take into account these obstacles and define strategies in order to overcome them successfully (especially in the context of environmental awareness).

5.2. Economic aspect

According to the studies reviewed, one of the major concerns expressed by the building owners/tenants was the predicted cost of renovations (Beillan et al., 2011; Johansson et al., 2017; Kamari et al., 2017). In the case study of Sweden, for example (Johansson et al., 2017), the payback period commonly exceeded 10–15 years due to relatively low energy prices and high labor costs, and such a time frame is commonly found to be unacceptable by real estate investors (Johansson et al., 2017; Lind et al., 2016; Popescu et al., 2012; Schade et al., 2013). However, several studies indicated that passive renovation measures have a low capital investment compared to the potential energy cost savings (Abro, 1994; Jafari and Haghighi Poshtiri, 2017). On the other hand, a study of renovation measures for a residential building in Singapore conducted by Sun et al. (2018) indicated that passive renovation measures were less cost-effective compared to active renovation measures (cost effectiveness was expressed as the ratio of annual energy cost savings and incremental cost). Within the study, the most cost-efficient measure proved to be the installation of energy-efficient lighting, followed by the renovation of air-conditioning systems. As for the passive measures, the authors found that the application of additional insulation levels, installation of energy-efficient windows, and the introduction of natural ventilation were not cost-effective—the price of the required renovation measures to reduce one unit of electricity was found to be too high. However, in countries with high personal incomes and extreme climates (such as GCC countries), the investment return period for building renovations is significantly shorter. For example, in a case study that evaluated passive renovation measures (additional thermal insulation and the installation of energy-efficient windows) for a residential building in Qatar (Kharseh and Al-Khawaja, 2016), the results suggested that based on the prices for the year 2016, the investment return period for the suggested renovation measures was between 0.5 and 4 years.

The cost-effectiveness of green roofs and green walls was addressed in multiple instances. Wong et al. (2003) compared the economic sustainability of intensive and extensive green roofs (intensive green roofs are designed as gardens, accessible to inhabitants and include paved seating areas, while extensive green roofs consist solely of greenery and are primarily designed in order to reduce energy use), and found that only extensive green roofs are cost-efficient due to lower investment and maintenance costs and higher energy savings. On the other hand, the study by Bianchini and Hewage (2012) found through a cost benefit analysis that both intensive and extensive green roofs are economically sustainable (however, it should be noted that the authors considered significant subsidies). Another study (Claus and Rousseau, 2012) also suggested that extensive green roofs are economically feasible only if public subsidies are available. Moreover, Claus and Rousseau (2012) noted that without subsidies, the private cost of an extensive green roof exceeds the benefits for the investor, even after taking into account the prolonged lifetime of the roof after the renovation. Carter and Keeler (2008) found that extensive green roofs could be more cost-effective than traditional roofs if lower construction material costs, increasing energy prices, and the inclusion of additional benefits are taken into consideration (such as storm-water protection). In an economic sustainability study by Perini and Rosasco (2013), both direct and indirect green walls were considered. In the case of direct green walls, greenery is planted in the base of the wall, and there is no vacant space between foliage and the building wall surface; in the case of indirect green walls, the greenery is planted in modular planting boxes fixed to the support structure a certain distance from the building wall. The results indicated that a direct green façade and indirect green façade with a support structure made of plastic could be economically sustainable due to achieved energy cost savings, low investment and maintenance costs, as well as a long lifetime (50 years). On the other hand, indirect green walls with a steel support structure proved to be economically unsustainable in all scenarios considered. As for the economic properties of various combinations of green roofs (intensive, extensive) and green facades (direct, indirect), all combinations proved to be economically sustainable if adequate tax incentives are available (Perini and Rosasco, 2016). However, the authors of the study noted that the combination of intensive green roofs and indirect green walls was on the edge of sustainability.

5.3. Environmental aspect

Generally, it is assumed that building renovations improve buildings' environmental performance due to the reduction in energy use. However, the building renovation process can be

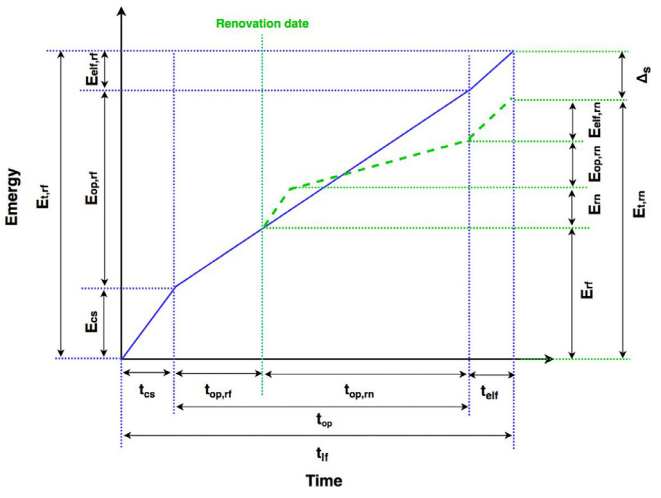

Fig. 4. Building environmental performance over its lifecycle (Andrić et al., 2017b).

environmentally intensive—it requires additional resources for the fabrication of renovation materials/systems, their transportation, and recycling/landfilling at the end of a building's lifetime. Thus, in order to assess the environmental performance of renovation measures, it should be evaluated as to what extent the renovation process contributes to a building's environmental footprint. This concept is illustrated in Fig. 4., and was previously developed by the authors of this study (Andrić et al., 2017b). In the reference case (without any renovations considered), during the construction, operation, and recycling/landfilling period (t_{cs}, t_{op}, t_{elf}), the building's environmental footprint is increased due to the materials and resources used in order to complete these processes (E_{cs}, $E_{op,rf}$, $E_{elf,r}$, respectably). However, if the renovations are performed at one point in the building's lifetime, from that point onwards to the end of the building's lifetime ($t_{op,rn}$), the building should have a lower environmental impact in its operation phase due to the reduced energy consumption $E_{op,rn}$. The environmental footprint would also be slightly increased due to the additional resources invested during the renovation (E_{rn}) and recycling/landfilling ($E_{elf,rn}$). If the reduction of the environmental impact caused by achieved energy savings is higher than the increase caused by additional resource investment (Δ_s), the building renovation improves building sustainability. Otherwise, renovation measures would increase the building's environmental impact.

Such an evaluation was conducted through an energy analysis of a renovation process for a residential building located in Serbia (Andrić et al., 2017b). Passive (additional insulation levels, energy-efficient glazing) and active (installation of solar thermal panels, connection to district heating system) technologies were considered, both as separate and joint measures. The results indicated that all the renovation measures considered reduced the building's overall environmental footprint, with the best results being achieved through a combination of active and passive measures (additional insulation levels + energy-efficient glazing + connection + solar-powered district heating). Finally, it was concluded that such building renovation measures improve overall building performance, lower the pressure on the local ecosystem, and improve the efficiency of indigenous resource use (Andrić et al., 2017b). A life-cycle assessment (LCA) study for a residential building in Switzerland (Lasvaux et al., 2015) that considered a combination of passive (thermal insulation) and active (ventilation system) measures found that the building's overall environmental impact was reduced after the renovations, despite the use of additional resources during the renovation phase. Another LCA study was conducted for the renovation of an educational building located in Spain (Sierra-Pérez et al., 2018), suggesting that the embodied impact of the building can be reduced by up to 70% through the use of passive renovation measures.

Environmental performance evaluations of green walls and green roofs is of particular interest—these renovation measures provide substantial energy savings, but also have higher environmental impacts compared to other passive measures since they require continuous maintenance over their lifetime (especially in the case of indirect green walls). A study that considered building renovations in a Mediterranean climate (Ottelé et al., 2011) through the application of direct and indirect green walls found that resources invested in the construction of a direct green wall and indirect green wall with planter boxes had a negligible contribution to the building's overall environmental impact. On the other hand, an indirect green wall based on a stainless steel support structure had a significant environmental impact. The environmental performance of a vertical greening system (direct green wall) was also considered in a study by Pan and Chu (2016), where a LCA study was conducted for the renovation of a residential building located in Hong Kong. Based on the study's findings, the authors concluded that due to the achieved energy savings, the building's overall lifecycle impact was reduced by -22–76% (depending on the impact category observed). Additionally, an energy-based analysis of direct and indirect green walls applied on a residential building in Italy suggested that the integration of such systems presents a sustainable operation for building retrofitting, and demonstrates that vertical greenery systems have a moderate and even balanced consumption of environmental resources (Pulselli et al., 2014).

As for the GCC region, there are not any reported examples and applications of green roof or green walls, however, a total lack of roofs in majority of building stocks can be taken as an opportunity to develop, experiment and implement a locally suitable effective roofing system to reduce heat load on buildings and hence reduce the cooling demand.

6. Conclusions

While global warming-driven changes of ecosystems could have multiple impacts on the built environment (the impact on building structures, building construction, materials, and indoor climate), the building sector presents significant potential for climate change mitigation – by reducing building energy consumption, significant reduction of greenhouse gas emissions and raw material extraction can be achieved. However, the relationship between climate change and building energy demand is reciprocal: changed climate conditions could affect the amount of energy used for heating and cooling services, and the reduction of energy used for heating and cooling could significantly contribute to climate change mitigation. According to the literature, buildings in hot and humid climates are most sensitive to climate change impacts — cooling demand could increase up to +150% while heating needs could decrease up to −264% (depending on the location and characteristics of the building observed). It should be noted that in these climates, cooling composes almost 90% of building energy demand—thus, total building energy demand could increase significantly (even if percentage-wise, the increase rate of cooling demand is lower than the decrease rate of heat demand).

Such an increase in overall demand and change in ratios between heating and cooling demand would have a significant impact on the operation of energy systems. In developing countries with a hot and humid climate (such as GCC countries), the majority of cooling services are provided by decentralized air-conditioning systems. Steep increases in demand would create additional stress on an already overloaded grid, resulting in failures and blackouts, which are already a frequent reoccurrence (impacting the business and operation of utilities and comfort of the consumers). Additionally, electricity production in these countries is solely fossil fuel-based and fossil fuel exports are currently the pillar of their economy—thus, an increase in self-consumption would increase the national emissions even more and also have a negative impact on their economy. Shift in demand would also impact the feasibility of district energy systems, which are widely considered as a more sustainable option compared to decentralized systems. However, if these systems are designed based on current climate conditions, they could become obsolete in the future, being overpowered (district heating systems) and underpowered (district cooling systems). Investing in new production units would increase the prices for consumers—and considering that stable prices are one of the reasons consumers connect to district energy systems, they could decide to disconnect from these systems, opting for other available technologies (such as heat pumps), impacting the feasibility of the systems.

Building renovation measures are commonly proposed as a mitigation measure against the increase in building energy consumption. Studies that considered the performance of building

renovation measures under future climate conditions found that passive and active renovation measures could reduce total building energy consumption by up to −38% (depending on the climate and building studied). Based on the studies available within the literature, incorporating vegetation into building envelopes (green walls) could significantly reduce energy demand due to the evapotranspirative effect. However, the performance evaluation of such a system under future climate conditions is not available within the current literature due to the current unavailability of green wall simulation software.

While renovation measures have significant potential for climate change mitigation, their large-scale application faces multiple challenges. Primarily, national renovation policies should be better defined, less ambivalent and diligently enforced. Suggested renovation measures within polices should not be defined as "one-size-fits-all," but rather adapted to the properties of different building stock segments. However, such a policy development requires detailed knowledge of the building stock. Based on current findings, the previous assumptions and data collection methods resulted in an underestimation of building energy consumption. However, new methods such as a combination of satellite and LiDAR imaging and GIS software yield promising results. Moreover, significant efforts should be invested into educating house owners/tenants and providing more information on renovation measures, as well as in motivating a system-thinking approach between the stakeholders and actors involved in the renovation process. Additionally, it is also relevant to account for the cultural background of house owners/tenants and their daily routines since these factors can influence the acceptance of renovation measures. Considering relatively low energy prices, long investment return periods (10–15 years), and the fact that the renovation process creates additional materials and resource consumption, the economic and environmental performance of the renovation measures proposed could be questioned. However, case studies suggest that the majority of passive and active renovation measures are economically and environmentally sustainable. The exceptions were intensive green roofs and indirect green walls with steel support structures. Such renovations that were measured proved to be on the edge of environmental sustainability and were economically unfeasible.

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